Ultra-heavy Yukawa-bound states of 4th Generation at LHC

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Abstract.
We present our study of bound states of the fourth generation quarks in the range of 500 to 700 GeV, where we expect binding energies are mainly of Yukawa origin, with QCD subdominant. Near degeneracy of their masses exhibits a new "isospin". We find the most interesting is the production of a color octet, isosinglet vector meson via $q\bar{q} \to \omega_8$. Its leading decay modes are $\pi_8^\pm W^\mp$, $\pi_8^0 Z^0$, and constituent quark decay, with $q\bar{q}$ and $t\bar{t}'$ and $b\bar{b}'$ subdominant. The color octet, isovector pseudoscalar π_8 meson decays via constituent quark decay, or to Wg. This work calls for more detailed study of 4th generation phenomena at LHC.

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1. Introduction

The fourth generation (4G), if exists, could play a crucial roles in electroweak symmetry breaking [1] and baryon asymmetry of the universe [2] due to their strong Yukawa couplings. Current experimental bounds on their masses are rather close to the unitarity bound (UB) of $500 - 550$ GeV [3], beyond which we enter strong-coupling regime [4] rendering perturbative approach inadequate. We present our study of early LHC phenomenology for possible *bound states* of 4G quarks by strong Yukawa couplings [5] in the range $500 - 700$ GeV.

The electroweak precision tests require t' and b' to be nearly degenerate, which institutes a new "isospin". This enables one to classify meson-like $Q\bar{Q}$ states: borrowing the QCD nomenclature we have ultraheavy isovectors π, ρ and isoscalars η, ω in color-singlet and octet modes.

Examining the existing studies from relativistic expansion [6] and relativistic Bethe-Salpeter approach [7], we identify ω_8, isosinglet, color-octet state to be most interesting for the early stage of LHC phenomenology. This is in clear contrast to the widely studied technicolor models where ρ–like state is usually the main signal.

2. Phenomenology of ω_8

To be consistent with the electroweak precision Higgs must be heavier than 600 GeV. QCD is subdominant at this scale. This leaves Nambu-Goldstone potential to be the dominant. Relativistic expansion and Bethe-Salpeter treatments show that the tightest bound state is π_1 followed by isoscalar vector meson ω_1. Their color-octet counter parts π_8 and ω_8 are the next lightest states. On the other hand this potential is repulsive for $\eta_{1,8}$ and $\rho_{1,8}$ making them most likely unbound. As far as LHC is concerned the production of color octet modes are more efficient due to strong interactions. The lightest two isovector states $\pi_{1,8}$ must be produced in pairs, while ω_1 is produced weakly. This leaves color-octet iso-

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singlet vector boson ω_8 to be phenomeno-logically the most interesting at least for earlier stage of LHC. Production cross section is estimated using the decay constant $\xi \equiv f_{\omega_8}/m_{\omega_8}$ and shown in Figure 1 along with open production of $Q\bar{Q}$ pair at LO and NLO. We see that the bound state production could be at the same order as open production even dominant at least for 7 TeV.

There are three types of decay channels : (i) Annihilation decay: $\omega_8 \to q\bar{q}$, $t\bar{t}$; $t\bar{t}'$, $b\bar{b}'$, (ii) Free-quark decay: $\omega_8 \to bW\bar{t}'$, $tW\bar{b}'$; (iii) Meson transition: $\omega_8 \to \omega_1 g$; $\pi_8 W$. We choose the following parameters

Figure 1. Production cross-section of ω_8 at the LHC running at 7 TeV (left) and 14 TeV (right) for various $\xi = f_{\omega_8}/m_{\omega_8}$ values.

for our numerical study: the decay constant $\xi = f_{\omega_8}/m_{\omega_8}$ of ω_8, ω_8 and π_8 mass difference Δm which signifies strong Yukawa binding, the third and fourth generation mixing $V_{t'b}$. We show the decay rates for four different cases: $\{\xi, \Delta m, V_{t'b}\} = \{(0.1, 100\text{GeV}, 0.1), (0.03, 100\text{GeV}, 0.1), (0.1, 200\text{GeV}, 0.1), (0.1, 100\text{GeV}, 0.01)\}$. Here we plot various decay rates for cases 1 to 4 in Figure 2.

For case 1, the dominant decay modes are the transition decay into $\pi_8 W$, especially for lighter mass region, and free quark decay. The branching ratios of free quark decay and the $V_{t'b}$-dependent annihilation (W boson exchange) decay increase with m_{ω_8}, due to larger Yukawa coupling. The $q\bar{q}$ is of order 10% and drops slightly at higher m_{ω_8}, with $t\bar{t}$ branching ratio a factor of 5 lower, at the percent level. The transition decay into $\omega_1 g$ is at the percent level or less.

For case 2, because of the small decay constant, the annihilation decay channels $t\bar{t}'$, $b\bar{b}'$, $q\bar{q}$ and $t\bar{t}$ are suppressed. In this case, free quark decay and transition decay into $\pi_8 W$ are the two predominant modes.

For case 3, the large mass differences enhance the branching ratio of the transition decays, and the $\pi_8 W$ mode dominates. The other transition decay into $\omega_1 g$ can also be enhanced, especially in the lighter mass region.

For case 4, the free quark decay and the $V_{t'b}$ induced annihilation decay are suppressed, due to small $V_{t'b}$. The decay width of 4G quarks is also suppressed for the same reason. In this case, the transition decay into $\pi_8 W$ dominates, and the annihilation decay into dijets can be sub-dominant with branching ratio at ten percent order. If $\pi_8 W$ becomes kinematically suppressed, dijets would be dominant.

In summary, the transition decay into $\pi_8 W$ is large, because of the large Yukawa coupling and no suppression effect by bound state deformation. This decay mode can be more enhanced if the mass difference is larger, but much suppressed for smaller value, especially if it is less than M_W. Free quark decay has a sizable contribution for the heavier mass region, if $V_{t'b}$ is close to the current upper limit of 0.1.

We have estimated the width of ω_8 and π_8 to be of order few GeV which makes them narrow resonances. For detailed discussion of π_8 decay modes we refer readers to Ref. [5]

3. Conclusion

We have presented our study [5] on possible ultra heavy bound states of 4G quarks formed due to strong Yukawa couplings in the range 500-700 GeV of heavy quark masses. If
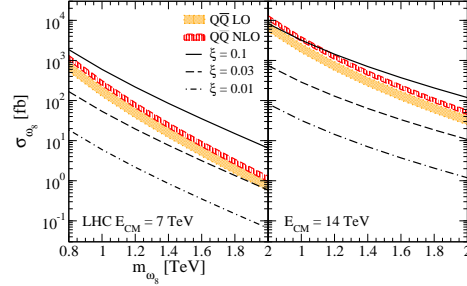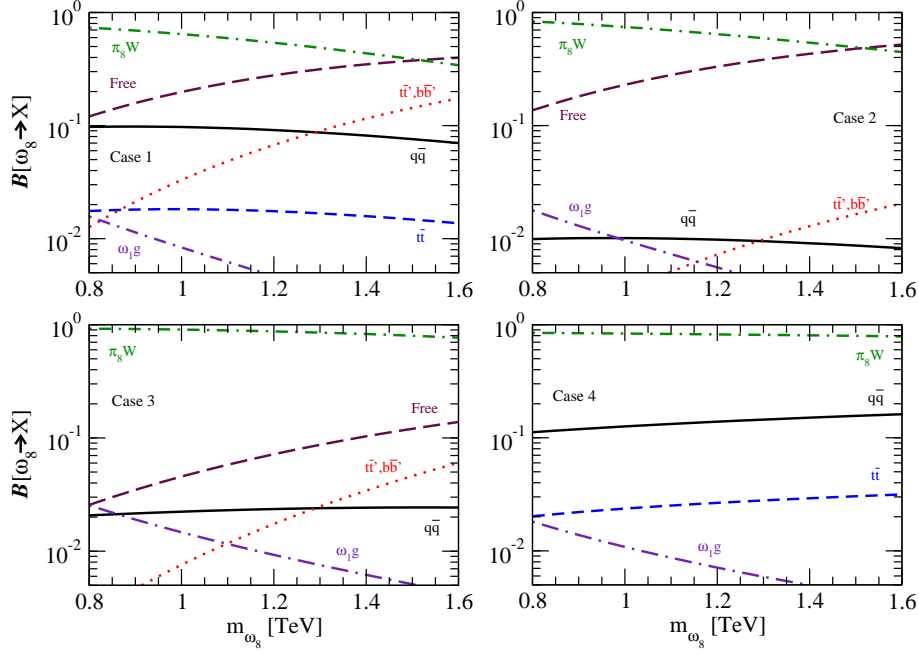
Figure 2. Branching ratio of ω_8 as a function of m_{ω_8} for case 1 to 4.

there are such bound states, while potentially interesting for LHC phenomenology, it will be also necessary to study their impact on the search of new generations. We show that, while being illustrative kind compared to the ongoing genuine non-perturbative lattice efforts [8], our study demonstrates importance of possible Yukawa-bound states.

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